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THESIS

SH-3 HELICOPTER/GLOBAL POSITIONING SYSTEM
INTEGRATION ANALYSIS

by

Robert Howard Hart

October 1982

Thesis Advisor: R. N. Forrest

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SH-3 Helicopter/Global Positioning System Integration Analysis

by

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Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN SYSTEMS TECHNOLOGY

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October 1982

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ABSTRACT

The Global Positioning System (GPS), the transmitted navigational signal, and the overall acquisition approach are explained. Navigational receiver components are functionally described and the hierarchy of platform integration and capability is discussed. Specifically explored is the integration of GPS into the Sikorsky SH-3 Helicopter. Performance comparisons of the medium versus high dynamic receiver, based solely on preliminary simulation data, indicate that at this time the medium dynamic receiver is the optimum configuration. Elimination of the doppler radar in lieu of the five channel receiver would only be possible after thorough over-water testing of the high dynamic set. The actual velocity accuracy of GPS receivers in a hovering helicopter is the main question yet to be answered. The overall mission effectiveness of the GPS equipped SH-3 Helicopter should be significantly improved because of an accurate, stand-alone navigation system.

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I. INTRODUCTION

A. BACKGROUND

There is general agreement that military users would benefit from global deployment of a precise navigation system. Precise positioning and navigation (POS/NAV) needs for the Department of Defense (DOD) have traditionally been satisfied by a multitude of specialized equipments responsible to particular mission requirements. The result has been a proliferation of POS/NAV systems producing an aggregate of system facilities and airborne, shipboard, and ground user terminals with varying degrees of accuracy and capabilities. Deployment of the Global Positioning System (GPS) will reverse this trend while providing accurate POS/NAV for all military users.

Generally speaking, the conduct of military operations requires that forces involved accurately know their position, velocity, and time. The missions assigned to the respective services generate a broad spectrum of unique yet in many cases, similar navigation requirements. The degree to which these requirements are satisfied directly affects the outcome of military ventures, particularly in multi-unit and joint service operations.

Global navigation requirements as stated by the Assistant Secretary of Defense For Communications Command, Control, and Intelligence are:

> "We need a system which can provide accurate navigation anywhere on the globe, one which is independent of ground stations, since we cannot be assured of the cooperation of countries enroute or in the vicinity of a crisis. We need a system which is accurate enough to serve as an instrument landing system, since we cannot be certain of the facilities which will be available at the airfields in a given crisis area. We need a system in which security is inherent in the design and does not compromise the existence or position of user." [Ref. 1]

The accomplisment of the following operational objectives during the GPS development testing phase has demonstrated the military value of a space-based navigation system.

1. C-141 and F-4 aircraft repeatedly made accurate approaches to uninstrumented runways utilizing only GPS information.
2. The pilots of an F-4 and a C-141 each used only cockpit steering displays driven by GPS to fly a passive, aerial rendezvous. Rendezvous accuracies were consistently achieved within the wingspan of the C-141.
3. Tests were conducted at sea, in the surf, and on the beach by a Marine Corps amphibious personnel carrier equipped with a GPS receiver. Test accuracies were in the 10 to 25 meter range, demonstrating the ability to penetrate through a narrow, mine-free corridor.
4. A C-141 twice demonstrated a parachute drop from 1,100 feet above the ground to within 20 meters of a drop

point identified in GPS coordinates by a GPS receiver on the ground. The C-141's navigator used only that information, his own GPS position, and wind data to compute the flight path and release point for the pilot. [Ref. 2]

The improved capabilities of such a system in terms of accuracy, common grid, global coverage, anti-jam, etc., significantly enhances mission effectiveness in a number of applications.

This discussion is limited to the Helicopter Anti-Submarine Warfare (ASW) environment and their proposed GPS user equipments. The reduction in the number of Helicopter Anti-Submarine Warfare (HS) squadron aircraft (from 12 to 6 SH-3H Helicopters) has significantly reduced the assets available for multi-unit ASW prosecution. Hence, precise POS/NAV are vital for successful mission completion in single helicopter operations.

B. ACQUISITION APPROACH

The acquisition approach for the GPS, recommended by the Defense Systems Acquisition Review Council (DSARC), is a step-wise, design-to-cost development and test program leading in successive phases to an operational Global Positioning System. Each phase is designed to build and expand on the previous phase in an integrated and cohesive manner. Phase 1, Concept Development, concentrated on validation of design concepts through Development Test and Evaluation (DT&E) of user equipment. Phase 2, Demonstration/Validation, will complete the DT&E and Initial Operational Test and Evaluation (IOT&E) of user equipment. Finally during Phase 3, Production/Development, the full GPS capability will be achieved. [Ref. 3]

Phase 1 encompasses the first of two design-build-test-design cycles to determine preferred user equipment configurations and validate life cycle cost models in the design-to-cost process. The purpose of this approach was to reduce overall program risk, to reduce projected user equipment design and life cycle costs through encouraging innovative designs, to increase industry competition by broadening the industrial base, and to fully investigate the potential classes of user equipment. Strong emphasis was placed early in these contracts on low development costs through the use of modular hardware and software designs, while total life cycle costs were minimized through the use of common modules across various host vehicle categories, wherever possible. [Ref. 4]

User equipment activities in Phase 2 are primarily concerned with development and testing of prototypes of user equipment. Two contractors are developing the basic set architecture for a family of user equipment hardware to be used in all classes of user equipment. This approach provides commonality across all classes of user equipment designed by each contractor and should achieve the desired cost benefits in Phase 3.

During Phase 3, the user equipment will move into full scale production. The family of user equipments which best meets the user's needs in terms of performance and cost will be selected for production.

The user equipments to be produced, as determined by individual user requirements, will be procured in large lot buys. Eventually, 20-30,000 sets could be deployed by the U.S. Military with a like number deployed by our allies. [Ref. 5]

In summary, the three phased development and deployment of the NAVSTAR GPS is an evolutionary process. Each step provides extensive legacy value for the next step. Throughout this process, system level testing will be accomplished in order to insure optimum system operation and emphasis will continue to be placed on obtaining information on the utilization of all types of user equipment for new military applications and tactics.

C. GLOBAL POSITIONING SYSTEM

The NAVSTAR Global Positioning System (GPS) is a space-based radio positioning and navigation system that will provide extremely accurate three-dimensional position (to within 16 meters spherical error of probability), velocity (to within 0.05 meters/second) and system time (to within 55 nanoseconds) to suitably equipped users anywhere on or near (within 500 miles) the earth. The GPS consists of three major segments: Space System Segment, Control System Segment, and User System Segment as shown in Figure 1.1. [Ref. 6]

The operational GPS Space System Segment deploys three planes of satellites in circular 10,898 nautical mile orbits, with an inclination of 63 degrees and a 12 hour period. Each plane would contain six satellites. This deployment will provide adequate satellite coverage for continuous and worldwide three dimensional positioning, navigation and velocity determination. Each satellite transmits a composite signal at two L-band frequencies consisting of a precision navigational signal and a coarse acquisition (C/A) navigational signal. The navigational signals contain satellite ephemerides (satellite positions), atmospheric propagation correction data, and satellite clock bias information provided by the Master Control Station (MSC). In addition, the second L-band navigation signal permits the user to determine the group delay due to the ionosphere or other electromagnetic disturbances in the atmosphere. [Ref. 7]

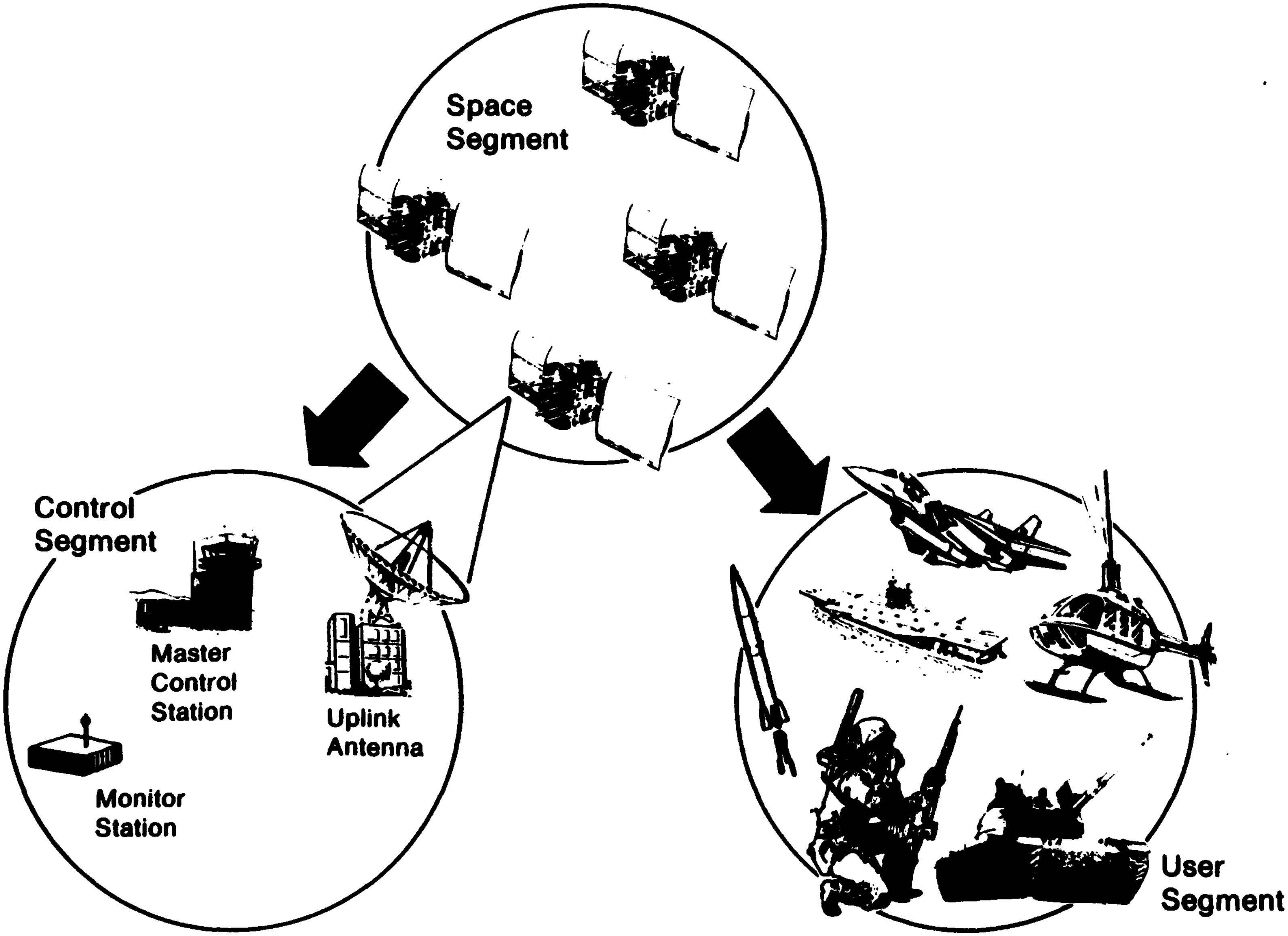


Figure 1.1 Global Positioning System Segments

The Control System Segment consists of four widely separated Monitor Stations that are located in U.S. territory or U.S. controlled territory. The stations passively track all satellites in view, and accumulate ranging data from the navigational signals. Ranging information is processed at a Master Control Station, located in the Continental United States, for use in satellite orbit determination and systematic error correction.

The orbit determination process derives progressively refined information about the gravitational field and solar pressure that influences the spacecraft motion, and the location, clock drifts and electronic delay characteristics of the ground stations. An Upload Station, located in the Continental United States, transmits the satellite ephemerides, clock drifts, and propagation delay data to the satellites as required.

Each satellite emits a carrier frequency which is modulated with a pseudorandom noise code of very low repetition rate. The generation of this code is synchronized to the satellite time reference. The user receiver also maintains a time reference used to generate a replica of the code transmitted by the satellite. The amount of time skew that the receiver must apply to correlate the replica with the code received from the satellite provides a measure of the signal propagation time between the satellite and the user. This time of propagation is called the pseudorange measurement since it is in error by the amount of time synchronization error between the satellite and receiver clocks. The receiver also measures the doppler shift of the carrier signals from the satellite. By measuring the accumulated phase difference in this doppler signal over a fixed time interval, the receiver can infer the range change increment. This measurement is called the delta pseudorange measurement and is in error by an amount proportional to the relative frequency error between the emitter and receiver clocks. Since the carrier wavelength is short, the delta pseudorange is a finely quantized measurement. [Ref. 8]

Using the navigation signals from each of four satellites, the user receiver/processor converts these pseudoranges and pseudorange rates to three-dimensional position and velocity, and system time. The position solution is in earth-centered coordinates, which can be converted to any coordinate frame or units of measure the user requires. To accomplish the navigation function, pseudorange and delta pseudorange measurements are used to update a running estimate of the user's position.

The NAVSTAR GPS Program is currently undergoing testing at the Yuma Proving Grounds Test Range utilizing satellite-type transmitters on the desert floor and a constellation of test satellites. A decision to deploy GPS could occur as early as late 1984. Space Shuttle launched satellites would then be in place by about 1987 along with initial deployment of military production user equipments. Civil usage is also expected to materialize in the late 1980s.

II. GPS USER EQUIPMENT AND INTEGRATION OPTIONS

A. SYSTEM COMPONENTS

The Phase 3 GPS User Equipment (UE) will be comprised of several integral components, each of which will be designed for usage on multiple platforms. These common components are referred to as Line Replaceable Units (LRU) which, in turn, are composed of a set of common hardware replaceable modules and chassis components known as Shop Replaceable Units (SRU).

This approach is consistent with the overall strategy of minimizing Life Cycle Cost by minimizing the number of platform unique elements, through the use of common modules, while satisfying the varying host vehicle unique requirements. The integration of GPS UE onto Navy/Marine platforms will be achieved by selecting the appropriate combination of LRU's necessary to meet the individual platform requirements. [Ref. 9]

The following provides a general description of the GPS User Equipment LRU's.

1. Antenna/Antenna Electronics

The antenna and antenna electronics are separate LRU's. There are two generic types of antennas available for use as part of the UE. They are:

1. Fixed Reception Pattern Antenna (FRPA)
2. Controlled Reception Pattern Antenna (CRPA)

The FRPA is a simple omni-directional antenna with a deep null at the horizon. The CRPA is a multiple element array antenna with "steerable nulls" that has a similar receiving pattern to the FRPA under ambient jamming and low level Radio Frequency Interference (RFI) conditions. Additionally, these "smart" antennas can sense jamming energy arriving from a specific direction and quickly adapt their receiving patterns to create nulls in those directions. The nulls are kept pointed towards the jammers, regardless of the vehicle's dynamics. The number of jamming sources that can be nulled is dependent on the number of antenna elements. The operation of the CRPA is self-contained and does not require any host vehicle information or interaction.

For helicopter applications, the antenna will be flush mounted on the upper fuselage (aft of the main rotor mast) with the antenna electronics mounted separately. No bottom mounted antenna is required due to the low dynamic flight maneuver characteristics of helicopters.

2. <u>Receiver Processor Unit (RPU)</u>

The RPU performs the signal and data processing. Three variations, each a separate LRU, are available:

1. High dynamic, fast signal acquisition (5 channel) - for high performance aircraft and submarines (SSN/SSBN)

2. Medium dynamic (2 channel) - for ships, helicopters, and medium performance aircraft

3. Manpack/vehicular (1 channel) - for infantry and vehicular operation

Each of the RPU's shall perform the following functions:

Receive and amplify signals transmitted by all visible satellites

Select and acquire signals from the four desired satellites

Track the acquired navigation signals (four simultaneously for the 5 channel, four sequentially for the 1 and 2 channel RPU's)

Extract information contained in the received satellite data

Measure the signal propagation error

Provide resistance to jamming

Compute position, velocity, and time (PVT)

Generate self test signals for UE fault isolation

Provide additional functions as required by platform configuration and mission (i.e., Inertial Aiding, Direct P Code Acquisition, etc.).

3. Flexible Modular Interface (FMI)

The Flexible Modular Interface (FMI) will perform the interfacing function between the RPU and the user platform. The FMI will provide the GPS UE with the capability of interfacing with analog and digital avionics equipment and may contain a microprocessor for data manipulation where required. The FMI for each platform will be designed to meet the unique requirements of that particular platform. These unique designs will be based on the strategy of utilizing replaceable components common to all FMI's. This functional partitioning approach will allow for commonality in the use of the other LRU's across many Navy and Tri-Service applications while supporting platform unique requirements in the platform unique FMI's.

4. Control Display Unit (CDU)

The GPS Control Display Unit (CDU) provides the operator with the capability to control the UE, input data, and observe UE generated outputs. The GPS CDU contains operating controls, a data entry keyboard, and alphanumeric displays.

For helicopter installations the GPS CDU will be mounted in the cockpit for pilot operation and viewing.

B. GPS USER EQUIPMENT CAPABILITY OPTIONS

A major variable in determining the specific LRU's required, the overall GPS User Equipment procurement, and individual platform installation and integration cost is the extent to which the GPS UE is integrated within the host platform. This in turn has implications regarding the existing platform capabilities which GPS will enhance, or the new capabilities it will provide to the platform. The proposed heirarchy of GPS User Equipment capability options available to the candidate platforms are:

1. Stand-Alone

This option provides stand alone GPS position and velocity data to the user. The baseline equipment required consists of:

a. Antenna/antenna electronics (FRPA)

b. Receiver/processor unit

c. Control/display unit

The impact of this integration is limited to the physical mounting of the equipment in the host vehicle. There is no software or hardware impact on the platform system due to the stand alone nature of this option. The CDU is the sole source of information entry and display.

2. Area Navigation and Instrument Landing

This option provides the capability to perform enroute waypoint navigation in which waypoints are either present or manually entered. In addition, instrument landing approach capabilities will be provided to determine deviation from course and glidepath as well as range and bearing to waypoints. The highly accurate GPS three dimensional position data could be used for non-precision instrument approaches to any airfield whose coordinates are known, including uninstrumented and temporary airfields. The baseline equipment required consists of:

a. Antenna/antenna electronics (FRPA)

b. Receiver/processor unit

c. Flexible modular interface

d. Control/display unit

The impact of this integration includes the physical mounting of the equipment and interfacing with the cockpit flight instruments via a switching assembly. The switching assembly will allow the pilot to select either TACAN or GPS signals to drive the cockpit flight instruments. There is no impact upon platform software.

3. <u>In-Flight Alignment and Calibration</u>

This option provides the capability of utilizing the GPS UE to update (damp) the platform on-board Inertial Navigation System (INS). Additionally, GPS UE could be used to align and calibrate the INS while in flight. The baseline equipment required consists of:

a. Antenna/antenna electronics (FRPA)

b. Receiver/processor unit

c. Flexible modular interface

d. Control display unit.

The impact of this integration includes interfacing with an INS for transmission of GPS data and appropriate modifications to the platform software. The extent of the inflight alignment capability is determined by the extent of the software modifications. In addition, this option is proposed to eliminate the need for a doppler navigation set.

4. Computer Update

This option provides the capability of utilizing the GPS UE navigation data to update the platform's Central or Weapons computer. This capability will enhance the functions of the systems interfaced to these computers. The baseline equipment required consists of:

a. Antenna/antenna electronics (FRPA)

b. Receiver/processor unit

c. Flexible modular interface

d. Control/display unit

The impact of this integration includes interfacing with the Central or Weapons computer for transmission of GPS data and appropriate modifications to the platform software. In addition, this option could be used to provide relevant Central or Weapons computer information to the GPS UE. This "feedback" is utilized as "aiding" information for the GPS during situations of reduced satellite visibility or intense jamming environments.

5. Anti-Jam Enhancement

This option provides the capability of enhancing the anti-jamming capabilities in the GPS UE, thereby providing accurate position and velocity data in a hostile environment. This capability can be achieved by using a CRPA vice FRPA antenna or by providing platform navigation sensor data to the GPS UE. The baseline equipment required consists of:

a. Antenna/antenna electronics (CRPA)

b. Receiver/processor unit

c. Flexible modular interface

d. Control/display unit

The integration impact of this option includes the installation of a CRPA and its associated electronics and an interface with the platform's inertial computer, central computer, and/or other on-board navigation sensors. If an interface between the GPS UE and the host vehicle's computers is required, a modification to the computer software would be necessary to provide the appropriate navigational data to the GPS UE. This option will also allow for a certain degree of "graceful degradation" of the GPS UE operation under hostile (jamming or high dynamic maneuvering) or adverse (reduced satellite visibility) conditions.

Implementation of this option could provide the platform with an anti-jam capability improvement of between 10 to 30 decibels. [Ref. 10]

C. SH-3 HELICOPTER INTEGRATION

The Sikorsky SH-3 helicopter is a single rotary wing, twin engine helicopter. It is configured to provide a close-in ASW capability to the carrier task force. This aircraft is the only Navy ASW platform equipped with a dipping sonar. The projected FY 89 SH-3 Avionics suite utilizes a tactical airborne navigation radio set (TACAN), standard cockpit flight instruments, an attitude heading reference system, automatic stabilization equipment (ASE), doppler navigation radar (AN/APN-182), and a tactical navigation system (TACNAV).

The TACNAV system accepts and processes inputs from the navigation and mission sensors for improved tactical maneuvering and crew coordination and displays the overall "tactical picture" on a cockpit display.

1. Integration Scope

GPS will be used as the primary source of navigation information in normal operation, and will provide a stand-alone area navigation and instrument landing approach capability. GPS will be integrated with the platform avionics suite to the extent necessary to support the above capabilities and allow for the "graceful degradation" of GPS UE operation under hostile or adverse conditions.

2. Integration Configuration

The planned implementation of the GPS User Equipment for the SH-3 helicopter will utilize the medium dynamic receiver (2 channel, sequential set) interfaced with the navigation computer (TACNAV), navigation sensors, and cockpit flight instruments.

The TACNAV will receive accurate navigation data from the GPS set, thus improving system performance. The TACNAV processor unit continuously computes the aircraft's present position for updating the tactical display and provides aircraft steering information. The present configuration uses doppler-derived ground velocity (from the AN/APN-182 Doppler), magnetic heading and true air speed for all navigational computations. The GPS UE shall provide drift velocity and heading velocity in an analog format equivalent to the doppler set. The TACNAV set's software and electronics interface are designed in modular form to accommodate platform equipment changes and updates. The TACNAV software will be impacted by this integration in that it receives direct inputs of position and time. This data can be used to relieve the TACNAV processor unit from its current time consuming navigational calculations and provide the crew with increased tactical capability. In addition, the TACNAV will provide waypoint and navigation data to the GPS UE for enroute navigation and operation of GPS in an aided mode. [Ref. 11]

GPS outputs will be interfaced with the cockpit flight instruments via a switching assembly which allows selection of either TACAN or GPS signals. Traditionally, TACAN has been used to establish relative positioning information regarding the accompanying forces. Can/should the GPS integration be slanted towards eliminating the TACAN? Since the SH-3 has no data link for position updating, all relative positioning concerning the accompanying units would be lost should TACAN be removed. The ramifications of this and its impact on the varied SH-3 Helicopter missions should be thoroughly explored prior to eliminating the TACAN equipment.

Additionally, the switching assembly will allow the pilot to select between baroaltimeter or GPS for the altitude hold function input to the ASE. The digital interface with the altitude/encoder provides "altitude aiding" which allows continued GPS operation when only three satellites are visible. The SH-3 GPS set will have improved anti-jamming capabilities with the integration of the navigation sensors and the inclusion of a Controlled Reception Pattern Antenna (CRPA) The proposed GPS UE for the SH-3 Helicopter is the following:

a. Controlled Reception Pattern Antenna (CRPA)

b. Receiver Processor Unit

c. Flexible Modular Interface

d. Control Display Unit

3. Integration Schedule

The integration into the SH-3 Helicopter will be performed in three stages: Research and Development, Procurement, and Installation. For all GPS UE platforms, the Research and Development stage will normally be performed over a three year period, the Procurement stage will require 18 months to 2 years, and the Installation stage will continue until the full complement of the platform type receives the GPS UE. [Ref. 12] The current integration schedule for the SH-3 Helicopter is:

1.	Research and Development	FY85-FY87
2.	Procurement	FY88-FY90
3.	Installation	FY90-FY92

III. RECEIVER/PROCESSOR COMPARISONS

A. RECEIVER EQUIPMENT ALLOCATION

The user's receiving equipment represents the end result of the Global Positioning System. High-performance systems, which may operate in conjunction with an inertial, or doppler air data unit, are designed to provide continuous navigation data even during violent aircraft manuevers in a severe jamming environment, or to provide a rapid initial position "fix" for a momentarily exposed submarine antenna. These systems track up to five different satellites simultaneously by having a receiver "tuned" to each desired satellite. This provides a near real-time solution. It is designed to work with one or two antennas; two antennas are needed in installations where satellite shadowing is severe due to platform dynamics. Since the ultimate user equipment cost is the most significant factor in determining whether or not GPS is a viable military system, it was important that the development phase provide another point on the cost versus performance trade-off curve. Many potential users don't need or are willing to give up the continuous tracking capability of the 5 channel set in favor of lower cost hardware; therefore parallel development of the sequential 2 channel receiver has been maintained.

As a joint service development program it was necessary to consider the requirements of all the military services while preserving minimum life-cycle-cost for all potential users. The initial design effort considered 30 different host vehicles, ranging from infantry and tanks to supersonic aircraft to ships at sea. To minimize life-cycle-costs, designs were needed that utilize the smallest number of unique hardware and software modules and still meet the totality of performance and host vehicle requirements. No one use should have to pay an inordinate share of the cost in order to satisfy the unique requirements of another user. In most cases, satisfying one user's requirements benefited all others.

The dynamic capability of the user platform was chosen as the "common denominator" for the allocation of particular GPS receiver equipments. The maneuverability of the unit is in most cases synonomous with the mission requirements. However, the helicopter has a unique flight regime, hovering, that requires some special consideration. Aircraft stability in a hover is relatively easy to achieve overland because of the availability of visual references for determining relative motion. Over-water hovering is quite a different situation. Wave action and sea swells continuously change the relative "picture" for the pilot and he becomes almost entirely dependent upon his instruments, especially at night.

Current helicopter stabilization systems utilize a doppler radar which can be electronically coupled to the flight controls via the ASE system. As aircraft movement is sensed, automatic flight control inputs attempt to eliminate the platform movement by "nulling" the sensed directional velocity through proper and timely control inputs.

The object of this thesis project was to explore the feasibility of utilizing the GPS velocity outputs for over-water hover control and platform movement sensing. Future implications could be the removal of doppler radar equipments from SH-3 helicopters and increased Search and Rescue (SAR) hover capabilities for all helicopters in night and inclement weather situations.

Considerable difficulty was experienced in acquiring detailed and precise performance data to allow quantitative comparisons of the proposed two channel receiver to the more desirable five channel receiver. The GPS Acquisition Program is just entering the Initial Operational Test and Evaluation (IOT&E) Phase. User Equipment prototypes are in the construction phase and have not yet been tested. Two channel sets were not utilized during the Concept Development Phase; therefore simulation data and preliminary studies were utilized to direct the research effort.

B. TERMINOLOGY

Prior to beginning a discussion concerning GPS Receiver Equipment performance, several terminology topics will briefly be explained.

1. Navigation Modes-Aided/Unaided

The extent to which the GPS UE is integrated into the host platform determines the level of aiding the GPS set receives. Aiding is necessary when satellite "shadowing" is encountered or when jamming signals interfere with normal signal reception. Sensor inputs from the host platform to the GPS UE allow for "degraded" operating mode of the equipment. During normal operating conditions, only satellite information is used for POS/NAV solutions. "Graceful degradation" of the system occurs when platform sensor data is used to augment the GPS solution because of insufficient satellite visibility or increased jamming interference. The term graceful degradation is often construed to mean a degraded operational capability when equipment failures occur. While this "crippled" operation occurs in some special circumstances, it is not a design feature of the manufacturers or a specification requirement.

2. Geometric Dilution of Precision (GDOP)

GDOP is a multiplicative term that degrades the accuracy of the receiver measurements due to the geometric positions of the "selected" cluster of satellites with respect to the user. The set initially tracks and collects ephemerides from all visible satellites and then maintains current ephemerides from subsequently visible satellites. Whenever the receiver fails to "find" a measurement from a satellite, the set selects a temporary replacement satellite, choosing an available satellite furthest in angle (180 degrees maximum) from the missing satellite. The replacement satellite is chosen without respect to constellation geometry and the receiver will periodically switch back to determine when the optimal satellite is available. However, the temporary GDOP is less desirable and increases navigational uncertainty results. The total User Equipment Receiver Error (UERE) is multiplied by the GDOP to determine the Spherical Error of Probability (SEP) in meters. The more desirable the GDOP, the smaller the numerical value of the GDOP.

3. Kalman Filter Process

Receiver/Processor set software consists of a multiple-state (11 or 12 states) Kalman filter for navigation processing. The states are three components each of position, velocity, and acceleration plus clock phase and frequency. The filter processes pseudorange and delta-pseudorange measurements, automatically "weights" platform sensor data in aiding situations, and may also process operator inputs when necessary. The outputs from the filter will be three components of position and velocity useable for display and platform integrated systems. The three acceleration components and clock phase and frequency are used internally for state propagation. The Kalman covariance is also available; it provides a "figure-of-merit" for indication of the quality of the navigation solution. The filter provides the capability of "graceful degradation" during periods of underdetermined measurements. The Kalman covariance also provides the receiver with a "search window" to preposition the sequencing set for its next satellite measurement. This involves providing an estimate of the pseudorange and delta-pseudorange rate at the beginning of the time of the next signal search.

C. NAVIGATION SIGNAL DESCRIPTION

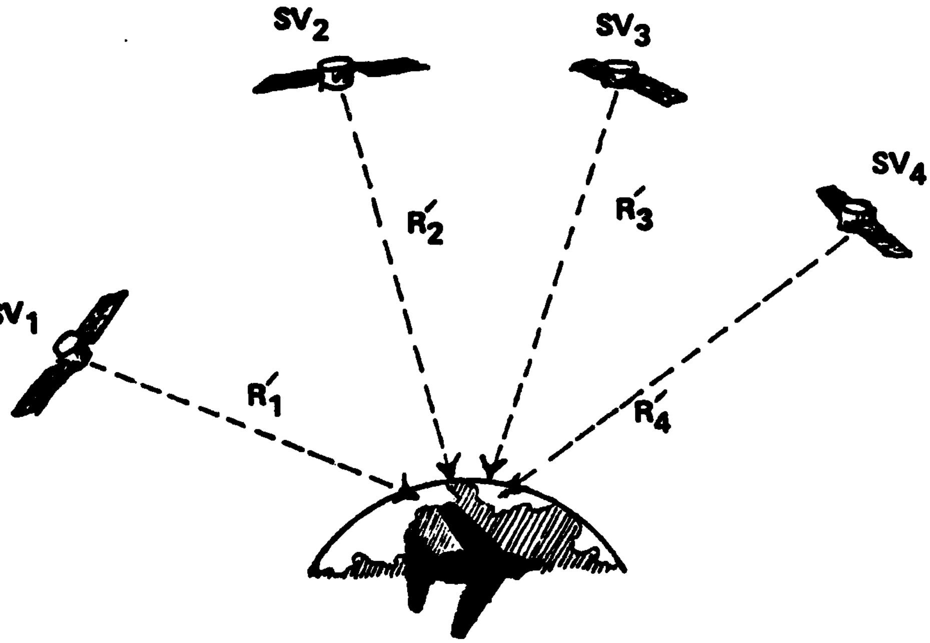
Each satellite in the GPS System radiates on two frequencies, 1575.42 and 1227.6 Mhz. Superimposed on these high frequency radiations are two uniquely coded signals: a precise or P-signal and a coarse acquisition or C/A signal. Also superimposed on these frequencies are the data signals used to determine system time and satellite ephemerides. The L1 signal (1575.42 Mhz) contains both the P and C/A-signal and is intended for the user who desires the ultimate in tracking precision and anti-jam performance. The L2 signal (1227.6 Mhz) contains only the P-signal for the purpose of ionospheric interference correction.

In GPS the reference points at any time are the satellite positions. To locate himself, a user must know his ranges to three satellites at that instant in time. If the transmitters send out "time-ticks", and if each of these ticks carries a time tag (i.e., the time it was transmitted), then by noting its time of arrival, the user can calculate the range.

Range = C x (arrival time - transmit time) where C = speed of light. This is the basis of GPS ranging. In order that it work, the transmitter and user clocks must be synchronized.

1. Pseudoranging

The calculated range will be in error by an amount proportional to the time error, call it Tb, if the transmitter and receiver clocks are not precisely synchronized. Then the ranging error, Rb, equals C(Tb). In GPS this is generally the case; the user clock is not initially or continuously synchronized to the precise time kept by the satellites. The user time bias, Tb, introduces another unknown into the solution of the location equations in addition to the three desired components of user position. To allow instantaneous calculation of these four unknowns, four independent measurements of range are required to four satellites as shown in Figure 3.1. Because of the time bias, the measurements are known as "pseudoranges."



WITH AN UNSYNCHRONIZED CLOCK, THE GPS USER MUST TAKE PSEUDORANGE MEASUREMENTS TO FOUR SATELLITES.

$$R'_1 = R_1 + ct_b$$

$$R'_2 = R_2 + ct_b$$

$$R'_3 = R_3 + ct_b$$

$$R'_4 = R_4 + ct_b$$

Figure 3.1 GPS Satellite Ranging

A type of signal modulation analogous to the time-ticks is that called pseudo-random-noise (PRN) bi-phase-shift-keying (BPSK) of the carrier. It consists of a carrier, the phase of which is periodically shifted forward or backward as determined by the instantaneous value of a very long sequence of ones and zeros. This sequence is called PRN code since, to the casual observer, the ones and zeros appear to occur in a random fashion. In actuality, the code generated is predictable, relative to the time it was started. The user can deduce when that code was transmitted by matching his own code to the incoming signal. The amount the user must shift his code to match the incoming signal determines the estimate of the time that signal took to reach the user, essentially the *pseudorange*. [Ref. 13]

2. <u>Precision and Coarse Codes</u>

a. The Precise Code

The P-code is a very long sequence of digital pulses which does not repeat itself for about 280 days. The pulse train of "ones and zeros" is created in a complicated set of shift registers, counters, and digital logic on board the satellite. The code is generated at about a 10 MHz chipping rate, where a chip is the time interval of either a zero or one in the pulse train. This means that each second, ten million "on/offs" are produced.

A unique portion (one week) of this long code is assigned to each of the GPS satellites. The receiver must distinctly discriminate among the many satellites it "hears" and selectively pick from those that are available. It does this through a correlation process which will be discussed rather briefly.

b. The Coarse Code

The C-code is a short sequence relative to the P-code and has a chipping rate one-tenth the P-code rate, or 1 MHz. The C-codes are chosen from a family of distinct codes (called gold codes). This assures minimum interference between satellites and unique satellite identification by the receiver is possible. The coarse code was chosen to assist users in reducing the time to acquire the longer P-code and for users who do not require greater accuracy (i.e., general aviation pilots), thereby reducing the cost and complexity of their equipment.

c. P-Code Acquisition

The long, high rate P-code is normally very difficult to acquire: i.e., to synchronize the user code generator to the incoming code. This process is called correlation. The usual technique in this case is to acquire a simpler signal first which, in turn, is closely synchronized to the long code. As it turns out, the C-code already described has the necessary properties. Hence, for the P-code users, the coarse signal acts as an acquisition aid. That signal is thus called the C/A (Coarse/Acquisition) signal.

d. Combining P and C/A Codes

Since the P and C/A codes are chosen not to interfere with each other (i.e., minimum correlation among the codes), they can be modulated onto the same carrier frequency in the satellites. Radio frequency transmitters are most efficient with constant amplitude signals. To produce that effect, the P and C/A carriers, though derived from the same source, are phase shifted ninety degrees apart, modulated by the P and C/A code and then combined. This signal addition, known as phased quadrature, produces a composite continuous wave (CW) signal at 1575.42 MHz.

3. System Data and Ionospheric Correction

Besides ranging measurements, the user needs to know where the radiating satellites are at any given instant in time. He also needs to know if the satellite signals are accurate relative to system time and, if not, how to correct for this offset. The method for transmitting all this information to the GPS user is to modulate the carrier with another signal. This additional signal contains the necessary system data.

a. System Data Information

The selected method for modulation of the carrier with satellite ephemeride information and system data is also biphase-shift-keying with the data stream. A low rate of 50 data bits per second (50 BPS) was selected. The total frame of data transmitted is 1500 bits. Thus the user initially takes 30 seconds to receive all necessary data from a single satellite. The data remains constant for a long period of time, typically up to one hour.

Relative to the ranging codes, the system data stream is very slow. It can thus be superimposed on the codes (and subsequently separated) without affecting operations of either the ranging codes or the data stream. The particular ranging code, P or C/A, and data stream are combined prior to modulating the carrier. The combination of the two digital signals in this way is called "modulo-2" addition. For convenience, the same set of data that is added to the P code is added to the C/A code and made available to all GPS users.

b. Ionospheric Correction Signal

During daylight, solar radiation produces a belt of ionized particles in a portion of the atmosphere known as the ionosphere, 40-300 miles above the surface of the earth. Signals passing through this region are refracted, resulting in longer than normal time delays. These time delays translate into ranging errors which, if uncorrected, can sometimes lead to relatively large position errors, depending on the GDOP.

The ionospheric effect has a predictable daily and annual pattern of variations. However, it is not a totally predictable phenomena. For high accuracy it cannot be completely modeled.

To permit an automatic correction of the ionosphere-induced ranging error, GPS satellites radiate a second signal at 1227.6 MHz. This L2 signal is modulated exactly the same as the L1-P signal and, of course, is time synchronized. The properly equipped user measures range on both the L1 and L2 signals at the same time and mathematically corrects for the ionospheric error.

Users not interested in the highest accuracy will choose not to implement the L2 signal. These users can make a partial, though less accurate, correction for the ranging error by a simple mathematical model.

4. Jamming and Interference Rejection

a. P-Code Performance

At the satellite transmitter, the P-code signal is broken down to a whole spectrum of frequencies which is spread over a band whose width is twice the chipping rate of the PRN code; (i.e., 20 MHz), hence the term spread spectrum. At the receiver, the process of correlating the receiver's code to the incoming code is simply the inversion of the modulating process, and the spread spectrum is collapsed back to the single frequency CW signal. Any CW jamming signal entering the receiver at the same time as the GPS signal is also processed the same way. The effect is that the jamming signal is spread over the 20 MHZ band, and its power density is greatly reduced, as shown in Figure 3.2. This "processing gain" is responsible for the superior anti-jam performance of the GPS spread spectrum signal.

b. C/A-Code Performance

The nominal processing gain of the short C/A-code is determined in much the same manner as that for the P-code. Since the chipping rate of the C/A-code is one-tenth that of the P-code, its processing gain is one-tenth that of the P-code. Hence, the jamming resistance of the C/A-coded signal is less than one-tenth that of the P-code signal for CW jamming because the C-code repeats 1000 times per second.

D. PERFORMANCE COMPARISONS

The satellite navigation signal was explained in considerable detail to provide an insight into the computational complexity of the signal selection and processing. A thorough understanding of the precise ranging scheme is necessary to comprehend the close correlation between performance accuracy and platform dynamics. The "combined performance of the system is defined to be the

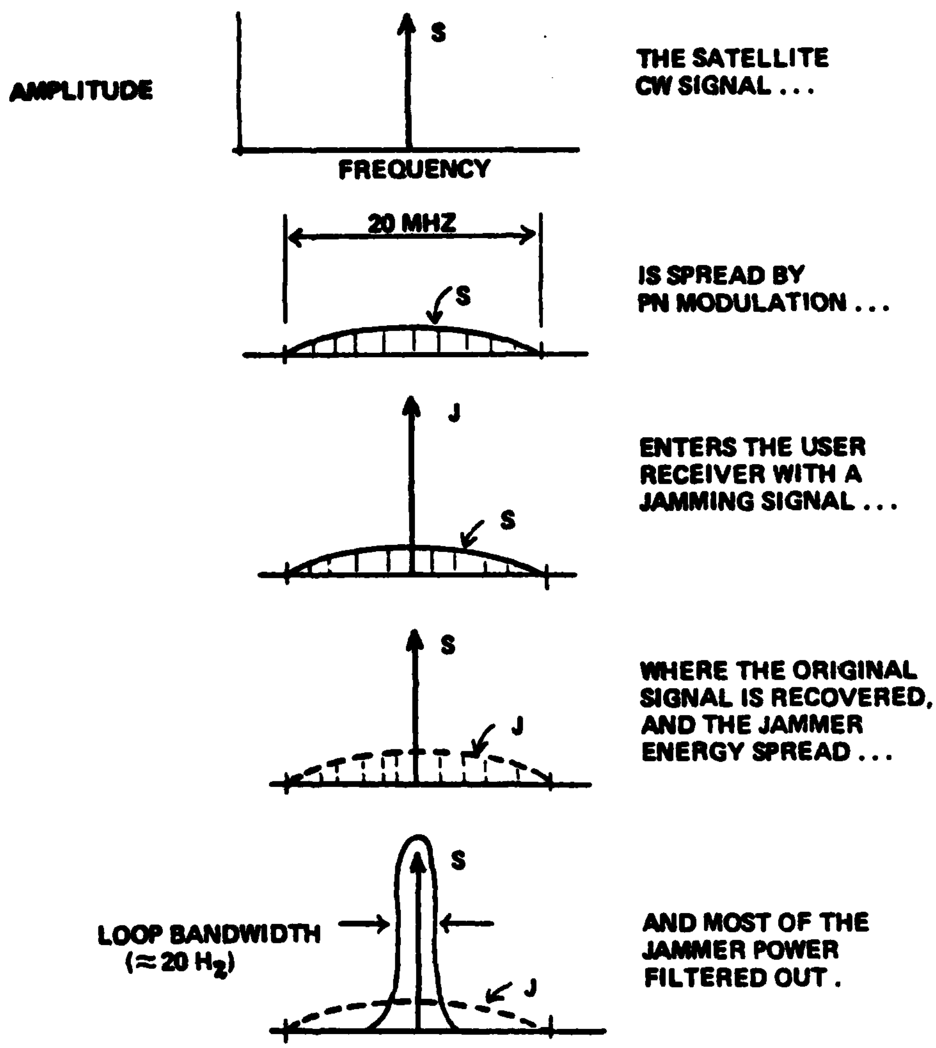


Figure 3.2 Spread Spectrum Processing Gain

simultaneously specified position/velocity/time (PVT) accuracy and jamming resistance and host vehicle dynamics that a GPS set is designed to meet". [Ref. 14]

All three receiver variations, high dynamic, medium dynamic, and manpack/vehicular, if placed in close proximity with no jamming present and stationary in position, will provide identical PVT information. Accuracy is enhanced if the User is stationary. The method of satellite selection, sequential or simultaneous tracking, is irrelevant in this motionless situation. However, the high dynamic 5 channel set will achieve its navigation solution much sooner than the other sets. The PVT agreement between the GPS sets will deteriorate upon the introduction of equipment motion into the scenario.

Assume that all three receivers are placed on a constantly accelerating platform. When the platform velocity exceeds 25 meters/second (approximately 50 knots) [Ref. 15], the manpack/vehicular receiver will be unable to "track" its own movement. The receiver cannot sequentially select the 4 necessary satellites quickly enough to solve the navigation problem. The two channel set, the medium dynamic receiver, will be overcome by dynamics at 400 meters/second (approximately 775 knots). [Ref. 16] The total combination of all platform dynamic movements (i.e., velocity, acceleration, jerk, yaw, pitch, roll) significantly impacts these performance threshholds for the receivers.

The sequential GPS sets must "time share" the receiver electronics. For example, in the two channel sequential set, the satellite ranging data is gathered from 2 satellites, then 2 other satellites are acquired, and their ranging information is computed. The delay involved may only be a few seconds in time (usually 1-2 seconds) yet can vary considerably in actual position, depending on actual platform velocity and direction. For example, a helicopter flying at 90 knots ground speed travels approximately 45 meters/second. A two second sampling interval means the "navigational fixes" are taken about 90 meters apart. The ranging values are fed into the Kalman filter in sequential order when they are calculated. The new data is "weighted" according to the Kalman filter gain and a running PVT solution is continuously computed. A consistent flight regime provides the most stable navigation solution. Qualitatively, the five channel receiver tracking 4 satellites simultaneously, almost "real time", has to be more accurate than the two channel set. Quantitatively, the question is, "How much better is it?"

1. <u>GPS Simulation Results</u>

The two channel set has only recently been assembled and has never undergone testing. Likewise, the prototype model five channel set has not been tested operationally.

Therefore, limited Monte Carlo type simulation data must be utilized for the performance comparisons of the receivers. Simulated GPS performance data of "unaided" receivers is shown in Figures 3.3 and 3.4.

These scenarios involve aircraft executing level turn maneuvers. In the five channel simulation, see Figure 3.3, the aircraft velocity is 1000 meters/second (approximately Mach 3). At time 30 seconds the aircraft executes a "5g turn" (100 meters/second/second rate of acceleration) which is completed at time 62 seconds. The East and North velocity errors never exceed .15 meters/second. The vertical velocity error appears to fluctuate almost randomly throughout the flight regime. In the two channel simulation, see Figure 3.4, the aircraft velocity is 100 meters/second (approximately 200 knots). At time 30 seconds, the aircraft executes a "2g turn" (20 meters/second/second rate of acceleration) which is completed at approximately time 62 seconds. Note that the vertical scale is an order of magnitude greater than the five channel simulation vertical scale. Maximum East and North velocity error is approximately 7 meters/second, over 40 times larger than that experienced with the five channel receiver. This maximum error is encountered only during the change in aircraft flight path parameters. Notice also that the 2 channel set velocity is accurately computed throughout the turn. The "transition out

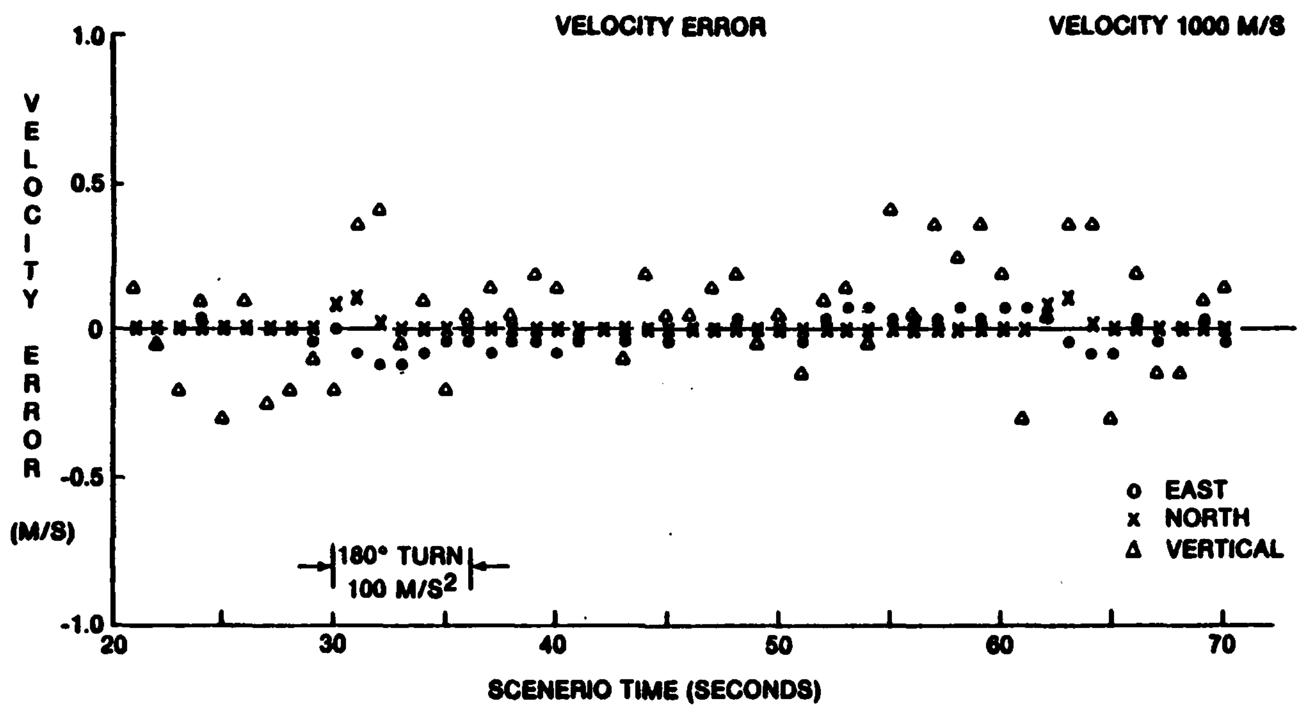


Figure 3.3 GPS Receiver Performance, 5 Channel

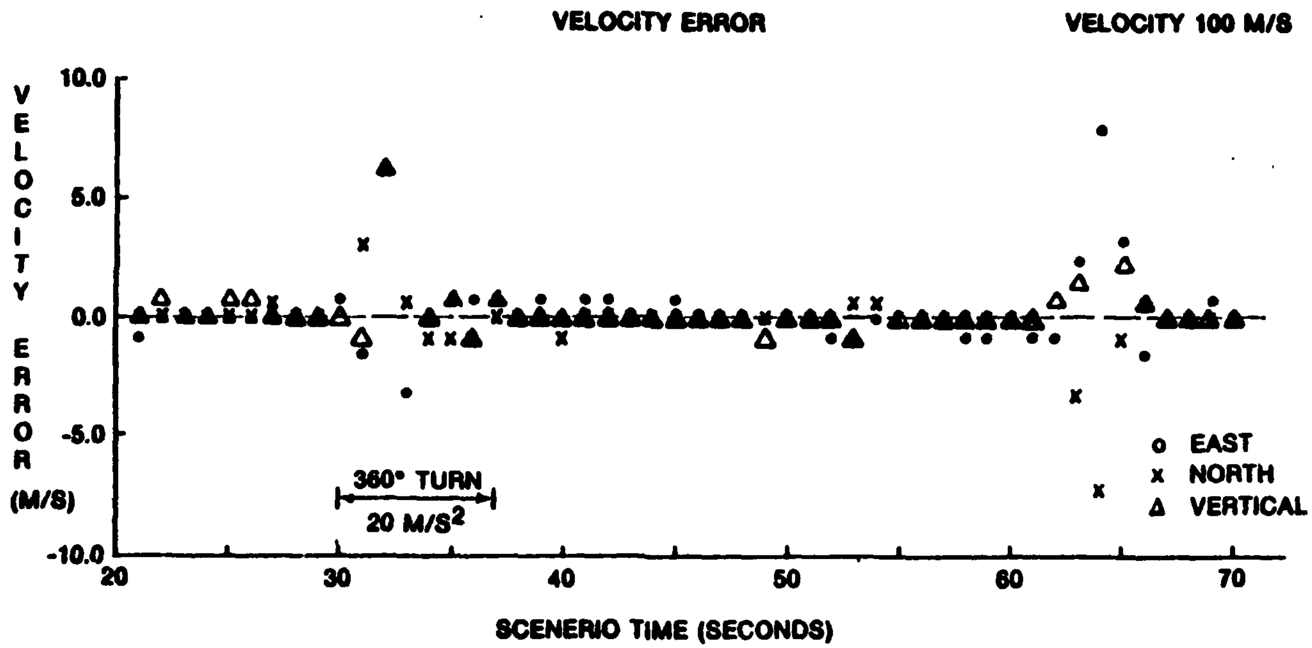


Figure 3.4 GPS Receiver Performance, 2 Channel

of the turn", at time 62 seconds, again disturbs the otherwise consistent tracking solution.

2. Discussion

It is this "transition state" that is of concern in the case of a hovering helicopter. Being inherently unstable, random helicopter movement constantly occurs while hovering. This is primarily due to wind speed and wind direction fluctuations and from automatic inputs to the flight controls through the ASE system. This movement typically is random in nature and partially responsive to perceived drift. This "closed-loop" system attempts to minimize the doppler measured drift velocities. Therefore, no consistent flight parameters exist except desired aircraft heading and zero velocity. The altitude parameter will be maintained with separate systems, the radar altimeter and a vertical accelerometer. The aircraft drift sensor must be able to ascertain small changes in actual platform velocity, (i.e., groundspeed), if it is to be utilized as part of the flight control stabilization system. Based on the available simulation data, the sequential receiver update rate of 1 to 2 seconds appears too slow to provide adequate information for automatic hovering requirements. The AN/APN-182 Doppler Radar accuracy for heading and drift velocity is .5% of ground velocity plus .5 kts at a refresh update rate of 10 times per second. Thus the doppler radar is quite accurate in low speed situations and provides data at a much faster rate than either GPS REceiver. The reliability of the AN/APN-182 Doppler is being significantly improved with the installation of a Solid State Transmitter Modification. This updated version of the doppler radar appears to be the better system for automatic flight control assistance.

Simulation data for 2 channel shipboard receivers (identical to the aircraft medium dynamic RPU) indicates that the Kalman Filter is unable to track and estimate the high frequency motions associated with the heave, surge, and sway of the ship. These motions pass through virtually directly as errors of from 1 to 3 meters/second. Similar gyrations in helicopter pitch, yaw, and roll necessitate a Kalman Filter sampling rate which exceeds the 2 channel receiver data rate. The changing of filter parameter values doesn't significantly alter the results concerning sampling rates. [Ref. 17]

The medium dynamic GPS receiver adequately satisfies the stand-alone area navigation requirement and is a major improvement over the current SH-3 positioning capability. The high dynamic GPS receiver is capable of "tracking" aircraft through high dynamic manuevers yet needs to be operationally tested to assess the hover enhancement it could provide.

E. PHYSICAL COMPARISONS

The physical characteristics delineated in the system specifications of GPS User Equipment Segment call for size, weight, and power consumption to be minimized. It states "no LRU shall exceed 18.2 Kg (40 pounds) in weight". [Ref. 18]

By upgrading the SH-3 Helicopter GPS Receiver from a 2 channel to a 5 channel RPU, the overall weight will increase from 4 to 10 pounds, depending on the selected contractor design. The equipment dimensions remain the same in height and width, only the length changes. An additional length of from 2 to 4 inches must be allotted for the RPU swap. All other LRUs are common to both configurations

Should hover testing of the five channel RPU prove the receiver accurate and reliable enough to eliminate the doppler radar, which weighs 70 pounds, an overall weight savings of 60 pounds would be realized.

Clearly, the size and weight variations encountered by installing the high dynamic receiver in the SH-3 are almost negligible. Therefore, the choice between the two or five channel receiver should be based primarily on performance and cost.

F. COST PROJECTIONS

There has been considerable discussion within the Global Positioning System Program concerning a proposal to replace all two channel receivers with five channel receivers.

Preliminary cost analysis figures for this proposal are based on receiver/processors only because the remaining LRUs (CDUs, FMIs, and Antennas) are identical in both system configurations.

The purchase of 14,663 five channel RPUs at an average unit cost of $40,870 equates to a projected production expenditure of 599.3 million dollars. The proposed mix of two/five channel receivers is 6478 two channel (average unit cost of $26,110) and 8185 five channel receivers (average unit cost of $43,440). The purchase of this mix would require a production expenditure of 521.7 million dollars. The five-channel-only alternative costs 74.5 million dollars (or 14%) more than the 2/5 channel mix. A slight savings per five channel receiver, approximately $2570, is realized due to larger production quantities but the differential cost between the individual 2/5 channel set causes a significant overall price increase. [Ref. 19]

A current Navy Postgraduate School thesis project is exploring in detail the overall life-cycle-cost benefits of the five-channel-only option versus the 2/5 channel mix.

IV. SUMMARY

A. CONCLUSIONS AND RECOMMENDATIONS

As stated earlier, the primary objective of the Global Positioning System is to provide continuous position and navigation information to all suitably equipped users. The primary mission of the SH-3 Helicopter is to provide close in ASW support to the carrier task force. Coordinated ASW operations with other aircraft or escort ships and secondary logistics requirements over long instances often require the SH-3 to depart the immediate task group area. The inabiility to accurately navigate from place-to-place in a stand-alone mode has alwayr been the paramount liability of the SH-3 Helicopter. Position information and the sensing of aircraft movement are dependent on the flow of doppler radar information. Any interruption or loss of doppler radar data degrades the navigational accuracy of the TACNAV Computer.

GPS could replace the doppler radar if the five channel receiver proves to be accurate enough, however, the unique, demanding coupler approach/hover requirements should have a backup system. The doppler and coupler system have performed well as a system and reliability should improve considerably with the updated transistorized transmitter modification. The GPS could be used as a backup to the doppler radar.

During conditions of a glassy sea state, the doppler radar sea return is insufficient for accurate processing and it indicates zero knots ground speed when the actual ground speed is often 30 to 60 knots. Only through keen observation of the flight instruments can the pilot ascertain the erroneous conditions. Comparison of the two system velocities and the actuation of an associated warning device when the difference threshhold is exceeded would enhance the safety of night and low visibility condition flight operations.

The rapid, dynamic response of the AN/APN-182 Doppler Radar is essential for the SH-3 Helicopter mission requirements. There is very little time or margin for error when hovering 40 feet above the water in instrument flight conditions. Rough seas and fluctuating winds also complicate the maneuver. Aircraft drift must be sensed immediately and corrective action taken accordingly. Even the five channel receiver data-update-rate is one-tenth that of the doppler radar. It is important to remember that the Global Positioning System, a navigational system, is being integrated into the SH-3 Helicopter.

Many Navy and Marine Corps helicopters do not have a doppler radar but are often called upon to perform search-and rescue missions in inclement weather. An aircraft drift instrument (velocity and direction) interfaced with the GPS receiver, could provide enhanced operational capability and lower crew risk in those emergency situations.

The GPS program rotary wing host vehicle for testing is the Sikorsky UH-60 Helicopter. Over-water testing is not presently programmed into the schedule. Over-land and over-water hover tests should be performed with both receivers to accurately assess their individual performance capabilities.

The SH-3 Helicopter GPS integration should be driven primarily by the potential operational mission advantages and secondarily by other side benefits. Until the GPS User Equipment is proven to be more accurate in velocity sensing than the AN/APN-182 Doppler Radar, the adequate integration configuration appears to be the medium dynamic receiver (the 2 channel set). The capability options that must be satisfied are stand-alone area navigation, instrument landing, and computer update for the TACNAV system. Should life-cycle-cost studies indicate significant savings or marginal additional expense for the five-channel-only option, the more accurate receiver would be a welcome addition to the SH-3 avionics. Currently however, the performance estimates do not justify the additional production costs which would be incurred in upgrading the SH-3 Helicopter GPS RPU from the two channel to the five channel receiver.

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